

New universality class of chiral symmetry breaking in the strongly coupled U(1) $\chi U\phi$ model

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We describe a 4D U(1) lattice gauge theory with charged scalar ϕ and fermion χ matter fields ($\chi U\phi$ model). At sufficiently strong gauge coupling, the chiral symmetry is broken and the mass of the unconfined composite fermion $F = \bar{\chi}\phi$ is generated dynamically by gauge interaction. The scalar suppresses this symmetry breaking and induces a line of second order transitions with scaling properties similar to the Nambu–Jona-Lasinio model. However, in the vicinity of a particular, tricritical point the scaling properties are different. Here we study the effective Yukawa coupling between the massive fermion and the Goldstone boson. The perturbative triviality bound of Yukawa models is nearly saturated. The theory is similar to strongly coupled Yukawa models except the occurrence of an additional state – a gauge ball of mass $m_S \simeq 1/2m_F$. This, and non-classical values of tricritical exponents suggest that at the tricritical point the $\chi U\phi$ model constitutes a new universality class. Nevertheless, it might be a microscopic model for the Higgs-Yukawa mechanism of symmetry breaking.

1. INTRODUCTION

Common mechanisms of fermion mass generation in QFT belong to one of the two generic types: First, the chiral symmetry is broken by the scalar field and the fermion mass is a consequence of the Yukawa coupling, like in the Higgs-Yukawa sector of the standard model. The four-fermion theory belongs to this type through universality, though the scalar field is auxiliary in this case. Second, the chiral symmetry is broken by a strong gauge interaction accompanied by confinement of the fermions acquiring mass, like in QCD or technicolor, or by a massless photon, like in the non-compact QED. No scalar field is involved.

A new generic mechanism, different from the above ones, has been suggested in Ref. [1]. The exemplary “ $\chi U\phi$ model” consists of a charged fermion field χ with strong vectorlike coupling to compact U(1) gauge field U , and a scalar field ϕ of the same charge.

In the $\chi U\phi$ model, the scalar field ϕ helps to solve two problems. First, it shields the fermion charge and gives rise to an unconfined, i.e. physical massive fermion $F = \phi^\dagger \chi$ in the phase with chiral symmetry broken dynamically by the gauge interaction (Nambu phase). Second, the scalar *suppresses* this symmetry breaking and at suffi-

ciently strong gauge coupling induces a second order transition to a chiral symmetric phase, thus opening a way to continuum. There is a particular point of the corresponding phase transition, a tricritical point, at which the model defines a new universality class.

We summarize the results of our extensive systematic investigations of this model in four dimensions by means of numerical simulations with dynamical fermions. The detailed account is given in [2,3]. Here we discuss the particular properties of the new universality class governing the tricritical point.

2. THE $\chi U\phi$ MODEL

The model is defined by the action

$$\begin{aligned} S &= S_\chi + S_U + S_\phi , \\ S_\chi &= \frac{1}{2} \sum_x \bar{\chi}_x \sum_{\mu=1}^4 \eta_{x\mu} (U_{x,\mu} \chi_{x+\mu} - U_{x-\mu,\mu}^\dagger \chi_{x-\mu}) \\ &\quad + am_0 \sum_x \bar{\chi}_x \chi_x , \\ S_U &= -\beta \sum_P \cos(\Theta_P) , \end{aligned}$$

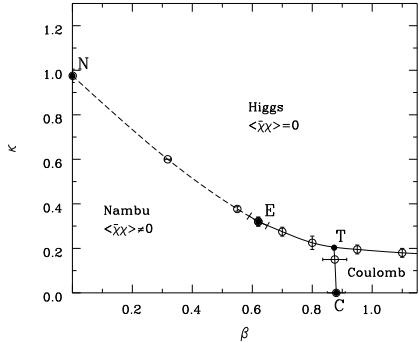


Figure 1. Phase diagram of the $\chi U\phi$ model in the chiral limit, $m_0 = 0$. The $\beta = 0$ limit corresponds to the NJL model. The NE line is a line of second order phase transitions. Other lines are lines of first order transitions. In the Nambu phase, chiral symmetry is broken dynamically and the fermion $F = \phi^\dagger \chi$ is massive.

$$S_\phi = -\kappa \sum_x \sum_{\mu=1}^4 (\phi_x^\dagger U_{x,\mu} \phi_{x+\mu} + h.c.).$$

Here $\Theta_P \in [0, 2\pi]$ is the plaquette angle. We use staggered fermions. The complex scalar field is constrained, $|\phi| = 1$. As its “hopping parameter” κ increases, it drives the model into the usual Higgs phase.

We note that there is no Yukawa coupling between χ and ϕ , as both fields have the same charge. The phase diagram at $m_0 = 0$ is shown in Fig. 1. Numerical simulations have to be carried out at nonvanishing m_0 and an extrapolation to the chiral limit $m_0 = 0$ performed.

3. TRICRITICAL POINT E

Point E is far away from any limit case and it does not appear to be accessible by any reliable analytic method, neither on the lattice nor in continuum. It is “tricritical” because in the full parameter space (including am_0) there are, apart from NE, two further second order “wing” lines

entering E from the positive and negative am_0 directions. The existence of a common point E of these three second order lines is neither predicted nor understood. The evidence is purely numerical, but quite strong [3]. Its position is $\beta_E = 0.62(3)$, $\kappa_E = 0.32(2)$.

The importance of the point E roots in the experience from statistical mechanics that a tricritical point belongs to a universality class different from that of any of the second order lines entering into it. The whole NE line except the point E corresponds to the same continuum model as the point N, the NJL model. The gauge field is presumably auxiliary and the model is therefore of limited interest there. However, the point E is expected to be different, gauge field playing an important role.

To verify this expectation, we have investigated critical exponents and spectrum of the model in the vicinity of E. Here we only mention the found value $\nu_t \simeq 1/3$ of the correlation length tricritical exponent. It differs from the prediction of the classical theory of tricritical points, indicating important role of quantum fluctuations at the point E [3].

4. SPECTRUM AT E AND ITS INTERPRETATION

Some insight into the physics of the continuum limit at the point E is provided by the spectrum and its scaling behavior. The massive physical fermion F , as well as other physical states, are composite. The interaction between them is due to the van der Waals remnant of the fundamental interactions. We shall attempt a possibly somewhat naive but illustrative interpretation of the found states in terms of the fundamental fields.

The fermion mass $am_F > 0$ decreases when the NE line is approached from the Nambu phase. The data are consistent with expected vanishing of am_F in the Higgs phase in the infinite volume limit. One can consider a simple composite picture of the fermion F and of its mass:

$$m_F \simeq \mu_\phi + m_\chi - E_B. \quad (1)$$

Here μ_ϕ is the mass of the scalar ϕ diverging at $\kappa = 0$. The constituent mass of the χ -fermion,

m_χ , is nonzero in the Nambu phase even in the chiral limit because of the chiral symmetry breaking. E_B is the binding energy, due to the gauge interaction between both constituents. When at fixed β in the Nambu phase the phase transition is approached by increasing κ , two things happen in (1): as ϕ gets lighter, μ_ϕ decreases and the chiral symmetry breaking is suppressed. Therefore also m_χ decreases. At critical κ the mass m_F in (1) vanishes. Above the critical κ , the mass m_F is zero like in the standard model with vanishing Yukawa couplings.

Further we find in the Nambu phase several $\bar{\chi}$, χ bound states. One of them is the obligatory pseudoscalar Goldstone boson π with the dependence on am_0 as required by current algebra.

Most interesting is the neutral scalar (S -boson). Its mass am_S vanishes on the wing critical lines, i.e. at the endpoints of the Higgs phase transition at small β . It is seen appearing as a composite of ϕ^\dagger and ϕ in the correlation function of the operator $O_1 = \phi_x^\dagger U_{x,\mu} \phi_{x+\mu} |_{scalar}$.

In the Higgs phase, at large β , S -boson can be identified with the Higgs boson as obtained in the unitary gauge. Below the confinement-Higgs phase transition, in particular in the Nambu phase, the interpretation of the S -boson is different. As the unitary gauge is no more applicable, one possibility is to see it as a $\phi^\dagger \phi$ bound state, i.e. as a “meson” consisting of two confined scalar “quarks”.

But it has been observed recently [3] that below the confinement-Higgs phase transition the S -boson shows up also in the gauge-ball correlation function $O_2 = \cos \Theta_P |_{scalar}$, as well as in the mixed correlation between O_1 and O_2 . The amplitudes are as large as in the correlation function of O_1 . On the other hand, a contribution of the S -boson to still another scalar channel, the $\bar{\chi}\chi$ one, has not been detected and is thus very small. In fact, no mass (“ σ -meson”) has been detected in that channel. Then a scalar gauge ball is expected to be the lightest scalar in the Nambu phase, because the $\phi^\dagger \phi$ bound state must get heavy when μ_ϕ grows with decreasing κ . This interpretation is supported by the fact that a light scalar is seen in the correlation function O_2 along the whole phase boundary ETC. Along TC it is

clearly a gauge ball.

Therefore we conclude that the new mechanism of chiral symmetry breaking we describe is accompanied by the presence of a scalar gauge ball in the spectrum.

5. MICROSCOPIC MODEL OF A YUKAWA THEORY

In the vicinity of the phase transition line NE we have determined the renormalized Yukawa coupling y_R between F and π . It is obtained from the three-point function of the corresponding composite operators and thus can be interpreted as an effective Yukawa coupling, which would describe the interaction between F and π in the regime where their composite structure can be neglected. We have found that at a fixed fermion mass am_F the Yukawa coupling increases when β decreases and the point E is approached.

In the interval $y_R \simeq 2 - 5$, where the Yukawa coupling is determined reliably, we have compared our results with the curve of maximal renormalized coupling, resulting from the first order perturbative calculation in the Yukawa model (triviality bound). It turns out that, close to E, the data are only slightly below such a curve. Therefore close to the tricritical point the $\chi U \phi$ model can be used as a microscopic model of an effective strongly coupled Yukawa theory [2].

We speculate that the suggested mechanism might be of some use for an explanation of the large top quark mass beyond the standard model.

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